

A NEW TYROSINE RECOMBINASE FOR GENETIC ENGINEERING

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1. INTRODUCTION

The present invention is directed to methods and compositions for TnpI-mediated genetic engineering using the *Bacillus thuringiensis* recombinase TnpI and the TnpI recombination substrates TRT or TRT', and variants thereof. In particular, the invention relates to TRT or TRT' sequences, and variants thereof, vectors, cells and kits useful for TnpI-mediated genetic recombination, as well as methods for the use of TRT or TRT' sequences for TnpI-mediated genetic engineering.

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2. BACKGROUND OF THE INVENTION

TnpI is a site-specific recombinase (SSR) encoded by the transposon Tn4430, a member of the TN3 family from *Bacillus thuringiensis*. TnpI belongs to the integrase family of SSRs, also referred to as the tyrosine recombinase family, and, as such, has structural similarities to other members of the integrase family of SSRs such as λ Int (Mahillon and Lereclus, 1988, EMBO J. 7:1515-26). It has been reported that TnpI mediates recombination of DNA molecules containing two relatively long DNA regions taken from Tn4430 in *Bacillus thuringiensis* (Salamitou *et al.*, 1997, Gene 202:121-26; Sanchis *et al.*, 1997, Appl. Environ. Microbiol. 63:779-84), and it was postulated to further require a host-derived factor (Mahillon and Lereclus, *supra*).

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Two site-specific recombinases of the tyrosine class, Cre recombinase from the *Escherichia coli* phage P1, and Flp recombinase from the *Saccharomyces cerevisiae* 2 micron episome, have opened a new dimension in the art of intentional genetic engineering in higher eukaryotes (Kilby *et al.*, 1993, Trends Genet. 9:413-21). Both recombinases recognize specific 34 bp recombination target sequences, called RTs. In the presence of active recombinase protein, only two corresponding RTs are required for recombination. The utility of these two recombinases lies in the fact that in both purified reactions *in vitro* and in living systems, other trans-acting factors or DNA sequence elements are unnecessary. By selected disposition of RTs and expression of the corresponding recombinase, precise genetic rearrangements can be effected in living cells.

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Although very useful, Cre and Flp recombinases may not be suitable for many genetic engineering applications. For example, Flp originates from yeast and consequently has a thermal optimum of enzyme activity at 30°C. However, it is not very efficient at

37°C (Buchholz *et al.*, 1996, Nucleic Acids Res. 24:4256-62), thereby limiting its applicability in genetic engineering to those hosts that grow in the appropriate temperature range. In addition, recombination reactions catalyzed by Cre and Flp are reversible, giving rise to partially rearranged DNA molecules. Other biochemical characteristics also impinge upon recombination efficiency, again potentially limiting host range (Ringrose *et al.*, 1998, J. Mol. Biol. 284:363-84). Thus it is important to identify new recombinases so that the genetic engineer can choose an optimal recombinase for use in the desired host organism.

Furthermore, there is great potential in genetic engineering for use of two, or more, recombinases in concert (Meyers *et al.*, 1998, Nat. Genet. 18:136-41). However this potential has not been developed, mainly due to the absence of a suitable combination of recombinases that are efficient in a given host. Although there are now more than two hundred candidate tyrosine recombinases in the databases, it is not possible to predict which candidates will be useful for genetic engineering by protein sequence similarity alone. Many of these greater than 200 candidates probably work in multi-protein complexes and require auxiliary factors for efficient recombination. Furthermore, in many cases, their RTs are not obvious and may not be short.

Thus there is a continuing need to identify new recombinases that work efficiently on short recombination targets and do not require auxiliary factors.

Citation of a reference herein shall not be construed as an admission that such is prior art to the present invention.

3. SUMMARY OF THE INVENTION

The present invention relates to compositions and methods for site-specific recombination using the recombinase TnpI, together with TnpI recombination target sites, either in a cell or in a cell-free system. The invention encompasses methods for *in vivo* and *in vitro* TnpI-mediated site-specific recombination, nucleic acid molecules, host cells and vectors that may be employed in such methods, and kits for use with such methods, nucleic acid molecules, host cells, and vectors.

The present invention is based on the discovery by the inventors of novel properties of TnpI and TnpI recombination target sites which are useful for genetic engineering. First, TnpI mediates recombination at two functionally distinct TnpI recombination target sites, herein identified as TRT and TRT'. TRT, the minimum 'core' TnpI recombination target site consists of a 32bp recombination target (RT) site, comprising two inverted repeat sequences. The larger TRT' is a 116 bp sequence comprising the core TRT as well as two direct repeat sequences. Second, TnpI mediated site-specific recombination using TRT and TRT' substrates can be accomplished both *in vitro* and *in vivo*, without requiring any

auxiliary factors. These previously unknown abilities of TnpI and its recombination substrates (referred to herein as the TnpI/TRT system) result in useful properties for genetic engineering.

In one embodiment, the invention provides a composition comprising an isolated
5 DNA molecule comprising one or more copies of TRT (SEQ ID NO:3) or a functional
variant thereof, with the proviso that the DNA molecule does not comprise the entire
sequence of TRT" (SEQ ID NO:4). In a specific embodiment, the DNA molecule
comprises one or more copies of TRT (SEQ ID NO:3), or a functional variant thereof, and a
heterologous nucleotide sequence. In other specific embodiment, the DNA molecule does
10 not comprise more than 32, 50, 100, 150, or 200 contiguous nucleotides of the sequence of
TRT" (SEQ ID NO:4). In another embodiment, the DNA molecule further comprises a
selectable marker. In another embodiment, the DNA molecule is a vector.

In another embodiment, the invention provides a composition comprising an isolated
DNA molecule comprising one or more copies of TRT' (SEQ ID NO:2), or a functional
15 variant thereof, with the proviso that the DNA molecule does not comprise the entire
sequence of TRT" (SEQ ID NO:1). In a specific embodiment, the DNA molecule comprises
one or more copies of TRT' (SEQ ID NO:2), or a functional variant thereof, and a
heterologous nucleotide sequence. In various specific embodiments, the DNA molecule
comprises one or more copies of TRT' (SEQ ID NO:2), or a functional variant thereof, with
20 the proviso that the DNA molecule does not comprise more than 116, 125, 150, 175, or 200
contiguous nucleotides of the sequence of TRT" (SEQ ID NO:4). In another embodiment,
the DNA molecule further comprises a selectable marker. In another embodiment, the DNA
molecule is a vector.

In another embodiment, the invention provides a cell transformed with a DNA
25 molecule, said DNA molecule comprising one or more copies of TRT (SEQ ID NO:3), or a
functional variant thereof, with the proviso that the DNA molecule does not comprise the
entire sequence of TRT" (SEQ ID NO:4). In another embodiment, the invention further
provides a cell transformed with a DNA molecule, said DNA molecule comprising one or
more copies of TRT' (SEQ ID NO:2), or a functional variant thereof, with the proviso that
30 the DNA molecule does not comprise the entire sequence of TRT" (SEQ ID NO:4). In
specific embodiments, the DNA molecule is integrated into the chromosome of the cell.

The invention further provides a eukaryotic cell transformed with a DNA molecule
integrated into its chromosome, said DNA molecule comprising one or more copies of TRT
(SEQ ID NO:3) or a functional variant thereof, or TRT' (SEQ ID NO:2), or a functional
35 variant thereof. In a specific embodiment, the cell is a mouse embryonic stem cell. In a
specific embodiment, the DNA molecule comprises two copies of TRT' (SEQ ID NO:3), or a

The invention further provides a method for effecting site-specific recombination in a non-*Bacillus thuringiensis* cell comprising exposing a first TnpI recombination target site and a second TnpI recombination target site to TnpI protein, under sufficient conditions and in an amount sufficient to mediate site-specific recombination between the first TnpI recombination target site and second TnpI recombination target site, wherein the first and second TnpI recombination target sites are selected from the group consisting of TRT (SEQ ID NO:3) or a functional variant thereof, and TRT' (SEQ ID NO:2) or a functional variant thereof. In one embodiment, this method further comprising, before said exposing, a step of introducing into the cell a first TnpI recombination target site and a second TnpI recombination target site. In another embodiment, the first TnpI recombination target site and the second TnpI recombination target site are on different DNA molecules. In an alternative embodiment, the first TnpI recombination target site and the second TnpI recombination target site are on the same DNA molecule. In another embodiment, the first TnpI recombination target site and the second TnpI recombination target site are in direct orientation. In another embodiment, the DNA molecule further comprises one or more non-TnpI site-specific recombination target sites. In yet another embodiment, at least one of the one or more non-TnpI sites is a Cre recombinase target site. In another embodiment, at least one of the one or more non-TnpI sites is a Flp recombinase target site. In a specific embodiment, the DNA molecule further comprises a heterologous nucleotide sequence, in the following order, from 5' to 3', the first TnpI recombination target site, a heterologous nucleotide sequence, and the second TnpI recombination target site, such that recombination between the first and the second TnpI recombination target site results in deletion of the heterologous nucleotide sequence. In another specific embodiment, the first TnpI recombination target site and the second TnpI recombination target site are in inverse orientation. In another specific embodiment, the cell contains a sequence encoding TnpI operably linked to a promoter. In another embodiment, the promoter is an inducible or tissue-specific promoter. In another specific embodiment, the cell is a eukaryotic cell, e.g., a mouse cell or an embryonic stem cell. In another specific embodiment, the first TnpI recombination target site and the second TnpI recombination target site are both TRT' sequences (SEQ ID NO:2) or functional variants thereof. In another embodiment, the first TnpI recombination target site and the second TnpI recombination target site are both TRT sequences (SEQ ID NO:3) or functional variants thereof.

The invention further provides a method of producing a circular DNA vaccine comprising: (a) introducing a DNA molecule into a non-*Bacillus thuringiensis* cell, said DNA molecule comprising, in the following order, from 5' to 3', a DNA sequence encoding an antigen of interest, a first TRT' site or functional variant thereof, an origin of replication

and, optionally, one or more selectable markers, and a second TRT' site or functional variant thereof; and (b) contacting said cell with TnpI protein under sufficient conditions and in an amount sufficient to mediate site-specific recombination between the first and second TRT' sites or functional variants thereof, such that recombination between the first and the second TRT' sites or functional variants thereof results in deletion of the origin of replication and the optional one or more selectable markers from the DNA molecule, such that a circular DNA vaccine encoding an antigen of interest is produced.

As used herein, the term "functional variant" of a TRT or TRT' sequence refers to a TRT or TRT' sequence with one or more altered nucleotide residues, such that the TRT or TRT' functional variant, when contained in a DNA molecule with a TRT or TRT', is capable of acting as a substrate for TnpI-mediated recombination, as assayed by an *in vivo* or an *in vitro* TnpI-mediated recombination assay. As used herein, the term "heterologous nucleotide sequence" refers to a non-Tn4430 nucleotide sequence.

4. DESCRIPTION OF THE FIGURES

Figure 1A-C. TnpI recognition target sequences.

1A. TRT" [SEQ ID NO:1], a 244 bp fragment containing a direct repeat of the sequence AAAATCAGA, an inverted repeat of the sequence TAATACAACACAAT, and a direct repeat of the sequence ACGCAACACAATTTAT.

1B. TRT' [SEQ ID NO:2], a 116 bp fragment containing an inverted repeat of the sequence TAATACAACACAAT and a direct repeat of the sequence ACGCAACACAATTTAT.

1C. TRT [SEQ ID NO:3], a 32 bp fragment containing an inverted repeat of the sequence TAATACAACACAAT.

Figure 2A-B. Sequence and structure of the transposon Tn4430

1A. A schematic diagram of the transposon Tn4430, with its 38 bp terminal inverted repeats (IR) represented by triangles and the position of the TnpI and TnpA (transposase) coding regions depicted as grey arrows.

1B. Sequence of the 249 bp TRT" [SEQ ID NO:4] indicating the following: the Tn4430 left IR (first shaded box); TnpI binding regions (open boxes), within which is shown the inverted repeats (black arrows), and the conserved 9 bp sequence (5'-CAACACAAT-3') common to all four TnpI binding sites; the direct repeats (grey arrows); and the TnpI translational start site (second shaded box).

Figure 3. The coding nucleotide sequence [SEQ ID NO:5] and the deduced amino acid sequence [SEQ ID NO:6] of TnpI'.

- 5 **Figure 4.** TnpI expression vector pYZ-BAD-TnpI, comprising a p15A replication origin, a kanamycin selection marker, arabinose-inducible promoter P_{BAD} , and *AraC*, the arabinose-responsive repressor that regulates P_{BAD} .

Figure 5. TnpI-mediated recombination in *E. coli*.

- 10 **5A.** Schematic representation of TnpI recombination substrate and products. The circular DNA starting material substrate (S) containing two directly repeated TnpI recombination target sites (arrows) and an origin of replication (filled circles). Recombination between the two TnpI recombination target sites produces two circular products (P), only one of which contains the origin of replication and is therefore capable of
15 replicating in the cell.

- 5B.** Agarose gel of products of TnpI-mediated recombination in *E. coli*. Plasmids contained either TRT or TRT' grown in *E. coli*, in either the presence (+) or absence (-) of TnpI expression. Lane 1: size marker. Lane 4: Plasmid containing TRT'-flanked sequence in the absence of TnpI. Lane 5: TRT'-containing plasmid recombination products after
20 recombination by TnpI (excised fragment lost during cell division). Lane 6: Plasmid containing TRT-flanked sequence in the absence of TnpI. Lane 7: TRT-containing plasmid recombination products after recombination by TnpI. (Lanes 2 and 3 are irrelevant.) Note high-molecular weight products not seen in the TRT'-containing plasmid. Positions of DNA fragments corresponding to the starting material substrate (S) and recombination
25 products (P) are indicated to the left of gel.

Figure 6. Overexpression and purification of TnpI.

- 6A.** Schematic representation of the relevant portions of the pGIV007 and pGIV008 expression vectors showing the pBAD::His-tag::*tnpI* and the pBAD::*tnpI* genes,
30 respectively. Positions of the start codons (ATG), the ribosome binding sites (RBS), and the restriction sites *NcoI* are indicated.

- 6B.** SDS-polyacrylamide gel electrophoresis showing the elution profile of the H-TnpI (top) and the TnpI (bottom) proteins from the nickel resin. The different lanes correspond to fractions that eluted at increased concentrations of imidazole as indicated. Arrowheads
35 show the position of the H-TnpI and TnpI proteins.

Figure 7. TnpI-mediated recombination *in vitro*.

- 7A. Schematic representation of the circular DNA substrate carrying directly repeated TRT (pGIV016) or TRT' (pGIV014) recombination sites (arrows). Recombination gives two circular products (P1 and P2) that can be distinguished from the substrate by restriction with *HindIII* (HdIII).
- 7B. Agarose gel (0.8%) of recombination reactions in the presence (+) or absence (-) of H-TnpI using, as substrates, plasmids carrying two copies of TRT (pGIV016, left panel) or TRT' (pGIV014, right panel). Positions of DNA fragments corresponding to the substrates (S1 and S2) and recombination products (P1 and P2) are indicated.
- 7C. Kinetics of recombination at TRT (squares) and TRT' (diamonds).

Figure 8. Topology of TRT and TRT' recombination reactions. Plasmid substrates incubated in the presence (+) or absence (-) of H-TnpI, and then treated in the presence (+) or absence (-) of DNase I, as indicated.

- 8A. Agarose gel (0.7 %) of TRT recombination products, yielding a DNase I ladder of catenanes containing 2, 4, 6, etc. nodes (shown to the right). Faint bands correspond to knotted products arising from multiple rounds of recombination.
- 8B. Agarose gel (0.7 %) of TRT' recombination products yielding a unique 2-noded catenane product.

Figure 9. Representation of a TnpI -TRT' complex. "Core" = TRT. "DR1" and "DR2" = direct repeat 1 and direct repeat 2.

- Figure 10.** Vector pSVpaT, comprising the SV40 promoter p_{SV40} , a puromycin resistance gene *puro* flanked by two 32 bp TRT sequences, the β -galactosidase gene *LacZ*, and a chloramphenicol resistance gene *cm*. pA indicates a polyadenylation signal.

- Figure 11.** Plasmid pCAGGS/TnpI, used to express TnpI in eukaryotic cells, comprises the constitutive chicken beta-actin promoter P_{CBA} , the rabbit beta-globin polyA- encoding sequence RBG pA, and splicing acceptor site sA.

- Figure 12.** TnpI-mediated recombination in eukaryotic cells. Diagram of the mouse ES reporter cell system cassette (top panel), containing a puromycin resistance gene, *puro*, flanked by TRT recombination target sites, and a non-expressed *lacZ* gene. Upon expression of TnpI from the plasmid pCAGGS/TnpI, the puromycin resistance gene is

excised and the *lacZ* gene placed under the control of the P_{SV40} promoter and expressed (bottom panel).

Figure 13. *LacZ* assay of mouse ES reporter cells expressing TnpI from pCAGGS/TnpI.

- 5 *LacZ* is expressed only when active TnpI is expressed within the ES reporter cell lines, as indicated by the dark (blue) cells.

5. DETAILED DESCRIPTION OF THE INVENTION

10 The present invention is directed to compositions and methods for TnpI recombinase-mediated genetic engineering. As discussed above, TnpI is a site-specific recombinase (SSR) encoded by the *B. thuringiensis* transposon Tn4430 (Mahillon and Lereclus, *supra*). Although previously thought to require a host-derived factor for
15 functionality, as demonstrated herein, TnpI requires only its specific recognition sequence contained in Tn4430 to mediate recombination.

The invention is based on the discovery by the inventors of the following novel properties of TnpI and its recombination target sites. First, TnpI mediates recombination at two functionally distinct TnpI recombination target sites, herein identified as TRT and TRT'. TRT, a 32bp recombination target (RT) site (shown in Figure 1C and described in
20 detail below), includes two inverted repeat sequences, the minimum 'core' recombination site. The larger TRT' is a 116 bp sequence, comprising the core TRT as well as two direct repeat sequences (shown in Figure 1B and described in detail below). As described more fully hereinbelow, both the recombination outcome and efficiency at these sites are
25 different. For example, recombination between two TRT sequences is 'unconstrained' (or 'relaxed') because it occurs freely between recombination sites, giving rise to all possible inter- and intramolecular DNA rearrangements *in vivo*, and a variety of topological products *in vitro*. In contrast, the direct repeats of the larger TRT' constrain recombination by
preventing intermolecular recombination events and favoring intramolecular deletion reactions between directly repeated sites. This 'constrained', unidirectional recombination
30 leads to the excision of sequences lying between the two TRT' sites. This previously unknown ability of the TnpI recombinase to mediate recombination reactions with different outcomes as a function of the structure of its recombination site is an unprecedented and useful feature for genetic engineering.

35 Second, TnpI mediated site-specific recombination using TRT and TRT' substrates can be accomplished both *in vitro* and *in vivo*, without requiring any auxiliary factors.

Thus, for example, TnpI mediated site-specific recombination can be used in eukaryotic cells, such as, for example, mouse embryonic stem cells ("ES cells").

Described herein are compositions and methods relating to the use of TnpI with these two TnpI recombination targets (also referred to herein as the TnpI/TRT system). The present invention relates to methods for the use of the TnpI/TRT system in eukaryotic or prokaryotic, non-*B. thuringiensis* hosts, the use of TRT and TRT' in conjunction with expressed TnpI to accomplish genetic rearrangements, including excisions from vectors and from cellular DNA, vectors and combinations of vectors to accomplish those excisions, and kits utilizing those vectors, cells, and methods. In particular, Section 5.1 describes compositions of the invention, including DNA constructs designed for site-specific recombination events using TnpI and a recombination target, and kits comprising such constructs. Section 5.2 describes methods for use of the invention, including methods for manipulation, excision, and integration of genes of interest into prokaryotic or eukaryotic host genomic DNA using TnpI and various genetic constructs that include a recombination target.

5.1 COMPOSITIONS FOR TNPI-MEDIATED SITE-SPECIFIC RECOMBINATION

Compositions comprising TnpI recombination target sequences useful for genetic engineering, including TRT', TRT, and sequence variants thereof, are described in detail herein.

First, the invention encompasses the minimum core recombination site TRT,

5'- TAATACAACACAAT[ATTA]ATTGTGTTGTATTA
[SEQ ID NO:3],

a 32 bp sequence comprising a pair of inverted repeats (underlined), also shown in Figure 1C. Recombination occurs by a TnpI staggered cleavage at symmetrical positions within this sequence, between the last two nucleotides at the 3' end of the repeat (*i.e.*, CACAA/T), resulting in a 6 bp central sequence, TATTAA), referred to herein as the 'central crossover region'.

The invention further encompasses the larger TRT', a 116 bp sequence comprising a the core TRT site and a pair of direct repeats (bolded):

5'- TAATACAACACAAT[ATTA]ATTGTGTTGTATTAGGTG
TTATAATAAATATAAATCTAGGGGTTTAACGCAACA
CAATTTATCGATAAATAAATACTTTTAGACGCAACA
CAATTTAT [SEQ ID NO:2],

which is depicted in Figure 1B.

For example, in various embodiments, sequences which may be altered include, but are not limited to, the TnpI binding sites, of the TRT central crossover region, or sequences within the TRT' spacer region. Such functional variant TnpI recombination target sequences may then be tested for TnpI binding and recombination activity *in vivo* or *in vitro*, in the various assays described in detail herein. In a preferred embodiment, such assays are used to select for functional variant TnpI recombination target sequences with increased binding affinity and/or recombination activity.

In one embodiment, for example, a TRT' functional variant is constructed comprising one or more altered nucleotide residues within the spacer region, which preserves the sequence of the core TRT site and the accessory direct repeats themselves. Such a functional variant TRT' sequence may then be tested for recombination activity *in vivo* or *in vitro*, as described herein. For example, in one embodiment, such a functional variant TRT' sequence comprises the following sequence:

15 5'- TAATACAACACAAT[ATTA]ATTGTGTTGTATTAGGTG
TTATAATAAATATATCTAGGGGTTTAACGCAACA
CAATTTATCGATAAATAAATACTTTTAGACGCAACA
CAATTTAT [SEQ ID NO:7]

wherein the altered nucleotide residue is underlined and in bold.

In another embodiment, a functional variant TRT' sequence comprises the following sequence:

20 5'- TAATACAACACAAT[ATTA]ATTGTGTTGTATTAGGTG
TTATAATATATATAAATCTAGGGGTTTAACGCAACA
CAATTTATCGATAAATAAATACTTTTAGACGCAACA
CAATTTAT [SEQ ID NO:8],

25 wherein the altered nucleotide residue is underlined and in bold.

In general, such a functional variant TRT' sequence may have the following general sequence:

30 5'- TAATACAACACAAT[ATTA]ATTGTGTTGTATTA[X₃₂]A
CGCAACACAATTTAT[X₂₀]ACGCAACACAATTTAT
[SEQ ID NO:9],

wherein X represents a nucleotide residue.

In another embodiment, a functional variant TRT' sequence may be constructed by modifying the length of the spacer between the core TRT site and the accessory direct repeats. For example, the spacer may be modified by the addition of one integral helical turn of the DNA helix, *i.e.*, 10 bp, or a multiple thereof, *i.e.*, 21 or 31 bp, for example. In

one embodiment, for example, nucleotide sequences having the following consensus sequence may be used as TnpI recombination targets:

5' - TAATACAACACAAT[ATTA]ATTGTGTTGTATTA[X₄₂]**A**
CGCAACACAATTTACGATAAAATAAATACTTTTAGAC
5 **GCAACACAATT**TA [SEQ ID NO:10],

wherein the underlined nucleotide residues depict the inverted repeats, bolded nucleotide residues represent direct repeats, and X₄₂, represents a spacer region sequence comprising an additional integral helical turn between the core TRT site and the accessory direct repeats.

Preferably, the accessory direct repeats are tenderly repeated on a same DNA molecule as the core TRT site. In another embodiment, the orientation of the direct repeats within the recombination target site may be manipulated. Reorienting the direct repeats can result in more complete removal of TRT sequences, which may be advantageous to genetic engineering applications. In alternative embodiments, for example, the orientation of the direct repeats may be forward, as depicted above, or reversed ("flipped") with respect to the inverted repeats.

The invention further comprises compositions with more than one copy of a TnpI recombination target sequence, such as TRT', TRT, or a functional variant thereof, on a single DNA molecule. Preferably, the DNA molecule comprises two TnpI recombination target sequences in tandem, separated by a variable length of heterologous sequence, recombination may occur between such TnpI recombination target sites. In one embodiment, such a DNA molecule comprises two TnpI recombination target sites, such as TRT', TRT, or a functional variant thereof, in direct repeat orientation. In another embodiment, such a DNA replicon comprises two TnpI recombination target sites, such as TRT', TRT, or a functional variant thereof, in inverted repeat orientation.

5.1.1 TNPI RECOMBINATION TARGET VECTORS

Vectors comprising TnpI recombination targets may be constructed. TnpI recombination target sites may be separated from each other by a nucleotide sequence, such as a nucleotide sequence encoding a selectable marker, or a nucleotide sequence encoding a gene of interest, such that recombination between the target sequence deletes or inverts the nucleotide sequence located between the two TnpI recombination targets.

In one embodiment, the vector comprises, in order: (1) a promoter; (2) a first TRT'; (3) a multiple cloning site (MCS); and (4) a second TRT', wherein the first and second TRT's flank the MCS. The MCS includes restriction enzyme cleavage sites that will enable the cloning of nucleotide sequences such that those sequences are controlled by the promoter. Upon introduction of the vector into a cell, and under the appropriate conditions,

embodiment, a vector is used that comprises a tissue-specific promoter operably linked to a TnpI-encoding nucleic acid, one or more origins of replication, and, optionally, one or more selectable markers.

- The chosen vector must be compatible with the vector plasmid described in Section 5.1.1, above. One of skill in the art would readily be aware of the compatibility requirements necessary for maintaining multiple plasmids in a single cell. Methods for propagation of two or more constructs in procaryotic or eukaryotic cells are well known to those of skill in the art. For example, cells containing multiple replicons can routinely be selected for and maintained by utilizing vectors comprising appropriately compatible origins of replication and independent selection systems (see Miller, 1992, A Short Course in Bacterial Genetics, Cold Spring Harbor Laboratory Press, NY, and references therein; and Sambrook *et al.*, 1989, *supra*).

5.1.3 VECTORS GENERALLY

- Circular vectors incorporating a TnpI coding region, or a region to be manipulated by TnpI, may be constructed using standard methods known in the art (see Sambrook *et al.*, 1989, *supra*; Ausubel *et al.*, Current Protocols in Molecular Biology, Greene Publishing Associates and Wiley Interscience, New York). For example, synthetic or recombinant DNA technology may be used. In one embodiment, a TnpI coding fragment is made by polymerase chain reaction ("PCR") amplification. In this method, oligonucleotides are synthesized to include restriction enzyme sites at their 5' ends, and PCR primer sequences complementary to the boundary sequences of a TnpI coding region at their 3' ends. These oligonucleotides are then used as primers in a PCR amplification reaction to amplify the TnpI coding region. This amplified region is then cloned into a vector containing an equivalent restriction site downstream of a promoter in such a manner that the promoter controls expression of the TnpI coding sequence. In another embodiment, a plasmid may be constructed to comprise two appropriately oriented TRTs or TRT' s flanking a gene segment to be excised or inverted, using standard molecular biology techniques (see *e.g.*, Methods in Enzymology, 1987, Volume 154, Academic Press; Sambrook *et al.*, 1989, *supra*; and Ausubel *et al.*, *supra*). The circular product is then transformed into *Escherichia coli* for amplification to yield large amounts of the vector.

- As TnpI-mediated recombination may be used in either prokaryotic or eukaryotic systems, the choice of vector construction depends upon the cell line or bacterial strain under study. For prokaryotic systems, the vector preferably includes an appropriate origin of replication and one or more selectable markers. For example, in plasmids maintained and used in *E. coli*, examples of appropriate origins of replication would be, without

limitation, ColE1-derived origins of replication (Bolivar *et al.*, 1977, Gene 2:95-113; see Sambrook *et al.*, 1989, *supra*), p15A origins present on plasmids such as pACYC184 (Chang and Cohen, 1978, J. Bacteriol. 134:1141-56; see also Miller, 1992, *supra*, p. 10.4-10.11), and pSC101 origin. Origins of replication may be selected for high (see Sambrook *et al.*, 1989, *supra*; see also Miller, 1992, *supra*, and references therein), medium (Bolivar *et al.*, 1977, Gene 2:95-113; see Sambrook *et al.*, 1989, *supra*), or low (Chang and Cohen, 1978, J. Bacteriol. 134:1141-56; see also Miller, 1992, p. 10.4-10.11) copy number per cell depending upon the particular application.

For the selectable marker, preferably antibiotic resistance markers are used, such as the kanamycin resistance gene from Tn903 (Friedrich and Soriano, 1991, Genes Dev. 5:1513-1523), or genes that confer resistance to other aminoglycosides (including but not limited to dihydrostreptomycin, gentamycin, neomycin, paromycin and streptomycin), the TEM-1 β -lactamase gene from Tn9, which confers resistance to penicillin (including but not limited to ampicillin, carbenicillin, methicillin, penicillin N, penicillin O and penicillin V). Other selectable genes sequences including, but not limited to gene sequences encoding polypeptides which confer zeocin resistance (Hegedus *et al.* 1998, Gene 207:241-249). Other antibiotics that can be utilized are genes that confer resistance to amphenicols, such as chloramphenicol, for example, the coding sequence for chloramphenicol transacetylase (CAT) can be utilized (Eikmanns *et al.* 1991, Gene 102:93-98). As will be appreciated by one skilled in the art, other non-antibiotic methods to select for maintenance of the plasmid may also be used, such as, for example a variety of auxotrophic markers (see Sambrook *et al.*, 1989, *supra*; Ausubel *et al.*, *supra*).

Any of the methods previously described for the insertion of DNA fragments into a vector may be used to construct expression vectors containing a chimeric gene consisting of appropriate transcriptional/translational control signals and the protein coding sequences. These methods may include *in vitro* recombinant DNA and synthetic techniques and *in vivo* recombinants (genetic recombination). Expression of nucleic acid sequence encoding a TnpI fragment may be regulated by a second nucleic acid sequence so that the TnpI protein or peptide is expressed in a host transformed with the recombinant DNA molecule. For example, expression of TnpI coding sequence may be controlled by any promoter/enhancer element known in the art. Preferably the expression is controlled by an inducible promoter. Inducible expression yielding a wide range of expression can be obtained by utilizing a variety of inducible regulatory sequences. In one embodiment, for example, the *lacI* gene and its gratuitous inducer IPTG can be utilized to yield inducible, high levels of expression of TnpI when sequences encoding such polypeptides are transcribed via the *lacOP* regulatory sequences. A variety of other inducible promoter systems are well known to

those of skill in the art which can also be utilized. Levels of expression from TnpI constructs can also be varied by using promoters of different strengths.

Other regulated expression systems that can be utilized include but are not limited to, the *araC* promoter which is inducible by arabinose (AraC) (see, e.g., Schleif, 2000, Trends Genet. 16:559-565), the TET system (Geissendorfer and Hillen, 1990, Appl. Microbiol. Biotechnol. 33:657-663), the p_L promoter of phage λ temperature and the inducible lambda repressor CI_{857} (Pirrotta, 1975, Nature 254: 114-117; Petrenko *et al.*, 1989, Gene 78:85-91), the *trp* promoter and *trp* repressor system (Bennett *et al.*, 1976, Proc. Natl. Acad. Sci USA 73:2351-55; Wame *et al.*, 1986, Gene 46:103-112), the *lacUV5* promoter (Gilbert and Maxam, 1973, Proc. Natl. Acad. Sci. USA 70:1559-63), *lpp* (Nokamura *et al.*, 1982, J. Mol. Appl. Gen. 1:289-299), the T7 gene-10 promoter, *phoA* (alkaline phosphatase), *recA* (Horii *et al.*, 1980, Proc. Natl. Acad. Sci. USA 77:313-7), and the *tac* promoter, a *trp-lac* fusion promoter, which is inducible by IPTG (Amann *et al.*, 1983, Gene 25:167-78), for example, are all commonly used strong promoters, resulting in an accumulated level of about 1 to 10% of total cellular protein for a protein whose level is controlled by each promoter. If a stronger promoter is desired, the *tac* promoter is approximately tenfold stronger than *lacUV5*, but will result in high baseline levels of expression, and should be used only when overexpression is required. If a weaker promoter is required, other bacterial promoters are well known in the art, for example, maltose, galactose, or other desirable promoter (sequences of such promoters are available from GenBank (Burks *et al.* 1991, Nucl. Acids Res. 19:2227-2230).

For eukaryotic systems, vectors will include eukaryotic-specific promoter regions, which include specific sequences that are sufficient for RNA polymerase recognition, binding and transcription initiation. Additionally, promoter regions include sequences that modulate the recognition, binding and transcription initiation activity of RNA polymerase. Such sequences may be cis acting or may be responsive to trans acting factors. Depending upon the nature of the regulation, promoters may be constitutive or regulated. Promoters that may be used to control TnpI expression include, but are not limited to, the SV40 early promoter region (Benoist and Chambon, 1981, Nature 290:304-310), the promoter contained in the 3' long terminal repeat of Rous sarcoma virus (Yamamoto *et al.*, 1980, Cell 22:787-797), the herpes thymidine kinase promoter (Wagner *et al.*, 1981, Proc. Natl. Acad. Sci. U.S.A. 78:1441-1445), the regulatory sequences of the metallothionein gene (Brinster *et al.*, 1982, Nature 296:39-42); plant expression vectors comprising the nopaline synthetase promoter region (Herrera-Estrella *et al.*, 1984, Nature 303:209-213) or the cauliflower mosaic virus 35S RNA promoter (Gardner *et al.*, 1981, Nucl. Acids Res. 9:2871), and the promoter of the photosynthetic enzyme ribulose biphosphate carboxylase (Herrera-Estrella

et al., 1984, Nature 310:115-120); promoter elements from yeast or other fungi such as the Gal 4 promoter, or the ADC (alcohol dehydrogenase) promoter.

Another option is to use a promoter that is tissue-specific, *i.e.*, one whose expression is preferentially activated within a particular tissue and results in the expression of a gene product in the tissue where activated. Tissue-specific promoters that may be used include the PGK (phosphoglyceroyl kinase) promoter, alkaline phosphatase promoter, and the following animal transcriptional control regions, which exhibit tissue specificity and have been utilized in transgenic animals: elastase I gene control region which is active in pancreatic acinar cells (Swift *et al.*, 1984, Cell 38:639-646; Ornitz *et al.*, 1986, Cold Spring Harbor Symp. Quant. Biol. 50:399-409; MacDonald, 1987, Hepatology 7:425-515); insulin gene control region which is active in pancreatic beta cells (Hanahan, 1985, Nature 315:115-122), immunoglobulin gene control region which is active in lymphoid cells (Grosschedl *et al.*, 1984, Cell 38:647-658; Adames *et al.*, 1985, Nature 318:533-538; Alexander *et al.*, 1987, Mol. Cell. Biol. 7:1436-1444), mouse mammary tumor virus control region which is active in testicular, breast, lymphoid and mast cells (Leder *et al.*, 1986, Cell 45:485-495), albumin gene control region which is active in liver (Pinkert *et al.*, 1987, Genes Dev. 1:268-276), alpha-fetoprotein gene control region which is active in liver (Krumlauf *et al.*, 1985, Mol. Cell. Biol. 5:1639-1648; Hammer *et al.*, 1987, Science 235:53-58); alpha 1-antitrypsin gene control region which is active in the liver (Kelsey *et al.*, 1987, Genes Dev. 1:161-171), beta-globin gene control region which is active in myeloid cells (Magram *et al.*, 1985, Nature 315:338-340; Kollias *et al.*, 1986, Cell 46:89-94), myelin basic protein gene control region which is active in oligodendrocyte cells in the brain (Readhead *et al.*, 1987, Cell 48:703-712), myosin light chain-2 gene control region which is active in skeletal muscle (Sani, 1985, Nature 314:283-286), and gonadotropic releasing hormone gene control region which is active in the hypothalamus (Mason *et al.*, 1986, Science 234:1372-1378).

Vectors that contain both a promoter and a cloning site into which a polynucleotide can be operatively linked are well known in the art. Such vectors are capable of transcribing RNA *in vitro* or *in vivo*, and are commercially available from sources such as Stratagene (La Jolla, Calif.) and Promega Biotech (Madison, Wis.). In order to optimize expression and/or *in vitro* transcription, it may be necessary to remove, add or alter 5' and/or 3' untranslated portions of the cloned DNA to eliminate extra, potential inappropriate alternative translation initiation codons or other sequences that may interfere with or reduce expression, either at the level of transcription or translation. Alternatively, consensus ribosome binding sites can be inserted immediately 5' of the start codon to enhance expression (see, *e.g.*, Kozak, 1991, J. Biol. Chem. 266:19867). Similarly, alternative

In another embodiment, DNA is delivered into the host cell by transduction of DNA that has been packaged into a phage particle. P1 or λ transduction and packaging protocols are known in the art. Lambda packaging extracts are available commercially (*e.g.*, from Promega, Madison, WI).

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5.1.4 CELLS USEFUL FOR TNP I-MEDIATED SITE-SPECIFIC RECOMBINATION

Compositions include prokaryotic and eukaryotic cells containing DNA molecules comprising TRT or TRT' sequences. Where genetic manipulations of nucleotide sequences of interest by recombination is desirable, it is useful to have ready-made cells available that can express TnpI to achieve recombination events. In prokaryotic cells, this may be accomplished by the integration of an expression cassette, consisting of a TnpI coding sequence operably linked to a promoter, into the host cell in such a manner that TnpI production is effected. This may be accomplished, for example, by using homologous recombination, transposon-mediated delivery systems, or λ integration to introduce the TnpI coding sequence into the host chromosome. Bacterial strains may also be engineered that carry a TnpI expression cassette on an episome or plasmid (see, *e.g.*, Salamitou *et al.*, 1997, Gene 202:121-26). Preferably, the promoter controlling TnpI expression is inducible.

The invention further relates to eukaryotic cells that contain at least one nucleotide sequence flanked by recombination targets, wherein the nucleotide sequence is excisable when TnpI contacts the recombination targets. The nucleotide sequence can be such that, upon TnpI-mediated recombination, the cell loses a gene function, gains a gene function, dies under certain conditions, or survives under certain conditions. The nucleotide sequence to be excised or inverted may be contained in an expression vector, a stable episome, or may be stably integrated into the genome of the host cell.

5.1.5 KITS

The invention also encompasses kits, comprising components useful for TnpI-mediated recombination packaged into suitable containers. Such kits include vectors suitable for the expression of TnpI in bacterial or eukaryotic cells, and may further include vectors suitable for the expression, and subsequent excision or inversion, of nucleotide sequences of interest, either by integration into the host genome or as episomes. Such kits may alternatively contain cells bearing DNA molecules with TnpI recombination target-flanked nucleotide sequences, as well as recombinant TnpI, or TnpI expression vectors for production of TnpI *in vivo*.

5.2 METHODS FOR USE OF TNP I-MEDITATED RECOMBINATION

The methods described herein relate to the use of TnpI with the specific substrate sequences TRT and TRT' for TnpI-mediated recombination. Such recombination can be used to delete or insert DNA sequences, resulting in modulation of gene expression. The methods may be used *in vivo* or *in vitro* for engineering prokaryotic or eukaryotic genes. Whereas recombination reactions with TRT substrates are fully reversible, recombination reactions utilizing TRT' are much less reversible. Thus, TRT sites may be used where reversibility of the reaction is desired. On the other hand, where greater stability is desired, stabilization of integration could be achieved using TRT (or a functional variant thereof) and transient expression of TnpI.

Generally, the methods described herein have the following common components: 1) a source of a functional TnpI protein, such as purified or recombinant TnpI recombinase or a cell or cell extract comprising comprising TnpI activity; and 2) a substrate comprising TRT or TRT', or functional variants thereof, optionally flanking a target nucleotide sequence of interest.

5.2.1 IN VIVO METHODS

The invention encompasses *in vivo* methods for the use of the TnpI/TRT system for genetic engineering of prokaryotic or eukaryotic genes. In general, such methods utilize DNA replicons, such as, for example, DNA plasmid vectors or chromosomal DNA which are specifically designed to comprise TnpI recombination target sites, *e.g.*, TRT or TRT' sequences, located at positions where recombination is desired to take place. Cells expressing TnpI activity, either constitutively or inducibly, are used as hosts for TnpI-mediated site-specific recombination. TnpI-mediated recombination may be used for deletion, insertion, or disruption of a gene of interest, or a particular domain of a gene of interest, or to make chromosomal alterations, such as large deletions and inversions, duplications and deletions by transallelic recombination, in inter- and intrachromosomal rearrangements (*e.g.*, to alter antibody specificity or receptor specificity in particular cell types). Specific embodiments of these methods are described in detail hereinbelow.

5.2.1.1 INSERTIONAL INTEGRATION OF DNA SEQUENCES

In one aspect of the present invention, TnpI-mediated recombination may be used to integrate new nucleotide sequences into a DNA molecule, such as an episome or genomic DNA. Targeted integration of DNA sequences into a eukaryotic or prokaryotic genomes may be used, for example, for expression of heterologous gene sequences in transgenic animals and plants.

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In one embodiment, for example, this may be accomplished by a two step process which involves the following steps. First, TnpI recombination target sites are introduced into the host genome, and second, a gene of interest is recombined into the genome at the TnpI recombination target sites via TnpI-mediated site-specific recombination. In a specific embodiment, insertion of one or more TnpI recombination target sites into the host genome may be accomplished by constructing an integration vector comprising two TnpI recombination target sites separated by a selectable marker. Preferably, the selectable marker is a negatively selectable marker, so that, in the second step, insertion of the gene sequence of interest can be selected by selecting against using the negatively selectable marker. Alternatively, naturally occurring TnpI recombination target sites, if they exist, may be used. In the next step, a gene sequence of interest, flanked by TnpI recombination target sites, is introduced into the host cell. TnpI is then expressed in the cell, allowing recombination at the TnpI recombination target sites, which results in insertion of the gene sequence of interest into the host genome between the TnpI recombination target sites.

5.2.1.2 REMOVAL OF DNA SEQUENCES

Another aspect of the present invention is the use of TnpI as a site-specific recombinase to delete nucleotide sequences of interest, such as, *e.g.*, selectable markers or other vector sequences, to disrupt gene function on an episome or in genomic DNA.

For example, in one embodiment, TnpI-mediated deletion reactions may be used for targeted excision of DNA sequences. In one embodiment, TnpI-mediated recombination may be used to delete a gene of interest from the genome of a higher organism. TnpI recombination target sites are inserted into the chromosome by homologous recombination flanking a gene of interest in direct repeat orientation. Expression of TnpI in such cells results in recombination at the TnpI recombination target sites and deletion of the gene of interest.

In a specific embodiment, the TnpI/TRT system may be used to create conditional knockout mutations *in vivo*, for example, in mice, in order to delete a desired gene sequence at a particular time or in a particular tissue. Such conditional knock-out mutations have been successfully produced using other site-specific recombinases, such as the Cre/lox system (for reviews, see Metzger and Feil, 1999, Current Opinion in Biotechnology, 10: 470-476; Sauer, 1998, Methods 14: 381-392). To this end, two directly repeated TnpI recombination target sites may be inserted into the genome by homologous and site-specific recombination in ES cells, such that the TnpI recombination target sites flank a gene of interest. Mice carrying such a "conditional" allele are crossed with TnpI-expressing transgenic mice. In the progeny, recombination will result in deletion of the gene of

5 In another embodiment, TnpI-mediated recombination may be used to remove unnecessary sequences from a DNA molecule after a genetic engineering step. For example, when a heterologous nucleotide sequence is integrated into a genome or an episome, extraneous sequences are often co-integrated, such as vector sequences required for replication, maintenance, or selection of the integration vector. After insertion of the

10 DNA sequence into the genome, such sequences are no longer necessary. Using the TnpI/TRT system of the present invention, such sequences may be removed. In a specific embodiment, for example, a mammalian cell line is transformed, preferably by electroporation, with a plasmid that contains a gene of interest and a selectable marker. The selectable marker is flanked by either TRT or, preferably, TRT' in the same orientation,

15 creating a TRT'-selectable marker cassette that is operably separate from the gene of interest. Once stable integration is accomplished, the host cell line is transfected with a vector containing a TnpI-coding sequence operably linked to a promoter suitable for transient expression of the TnpI gene. Upon expression of TnpI, the selectable marker is excised from the genomic DNA, leaving the gene of interest intact.

These methods are useful, for example, for the purposes of gene therapy or any application aiming at producing food-grade genetically modified organisms (GMOs). In these applications it may be desirable to introduce into a genome a particular functionally-modifying gene, without the associated vector sequences that were required for maintenance of a vector in a bacterial host. Such sequences may be removed using the TnpI-mediated deletion reaction described herein. In another embodiment, marker sequences used for selection of recombinants may be removed. Specifically, a vector comprising: 1) a eukaryotic gene of interest, 2) a bacterial selectable marker, and 3) origin of replication is used to transform plant cells, by homologous recombination of the gene into the cellular DNA. For genetically-modified plants, the eukaryotic gene is desirable, but the origin of replication and selectable marker, which in the field may be transferred horizontally to sensitive bacteria, are particularly undesirable. To remove these unwanted sequences after introducing the gene of interest, a plasmid vector is constructed comprising: (1) a gene segment to be integrated into the plant cells' genomic DNA; (2) a bacterial host-relevant selectable marker, and (3) two TnpI recombination target sites that flank the selectable marker and origin of replication in such a manner that, when recognized by TnpI, the bacterial-relevant genes are excised. The vector is linearized and transformed into the new

host cells. Once integration and expression of the desired gene has occurred, the bacterial-relevant marker and origin can be removed by TnpI-mediated recombination, as described above.

5 TnpI-mediated recombination *in vivo* can also be used to disrupt gene function. This can be accomplished by inserting one or more TnpI recombination target sites in or adjacent to an endogenous gene of interest, whose function is desired to be disrupted. TnpI is then expressed in the cell, resulting in recombination between the TnpI recombination target sites, a concomitant loss of gene function. Preferably, TnpI is expressed by induction of TnpI residing on a plasmid under the control of an inducible promoter. Preferably, the
10 plasmid contains an appropriate origin of replication conferring medium copy number to high copy number, and a gene that confers resistance to an antibiotic to which the host is sensitive.

In a specific embodiment, for example, a prokaryotic host capable of expressing TnpI as above is used. The second plasmid contains, in order, a selectable marker, a
15 recombination target, a second selectable marker oriented so as to be transcribed in a direction opposite to that of the first selectable marker, a second recombination target, and a promoter in the same orientation as the first selectable marker and capable of driving expression of the first selectable marker upon recombination. Preferably the selectable markers confer antibiotic resistance, but may also confer prototrophy to the appropriate
20 auxotrophic strain. Prior to recombination, only the second selectable marker is expressed. Upon expression of TnpI, however, the second selectable marker is excised and lost; the excision joins the promoter and first selectable marker, which is then expressed.

5.2.1.3 INDUCTION OF GENE EXPRESSION

25 In another aspect of the invention, TnpI-mediated site specific recombination may be used to modulate, *i.e.*, increase or decrease, the expression of specific genes within a host cell. In one embodiment, a vector is constructed comprising a promoter, a gene of interest, and a spacer sequence separating the promoter and the gene of interest such that the promoter is not operably associated with the gene and no expression occurs. The spacer
30 sequence is flanked by two directly repeated TnpI recombination target sites. When TnpI is expressed in the cell, recombination between the target sites results in excision of the spacer. This results in the promoter becoming operably associated with the gene of interest, inducing in gene expression. If desired, the spacer region may comprise a selectable marker, preferably a negative selectable marker, so that removal of the spacer region may be
35 selected for. In this embodiment, TnpI expression can be accomplished in a number of different ways, including introducing an expression vector that expresses TnpI, in an

5.2.2 IN VITRO METHODS

- The invention also encompasses *in vitro* methods for genetic engineering of prokaryotic or eukaryotic genes. In these methods, a purified or isolated TnpI activity is supplied to a substrate DNA molecule comprising TRT or TRT' sites. Preferably, purified recombinant TnpI is used. The substrate DNA molecule used in these *in vitro* methods comprises a DNA molecule containing two directly repeated TRT or TRT' sites, between which sites resides a target nucleotide sequence whose rearrangement is desired, *i.e.*, the target sequence to be deleted or inserted into a second substrate molecule. The substrate is preferably a supercoiled DNA molecule.
- In one embodiment, for example, *in vitro* TnpI recombination reactions are performed as follows. A supercoiled DNA plasmids containing two copies a functional TnpI recombination target site sequence is used as a recombination substrate. Recombination reactions are performed in 20 µl volume using approximately 500 ng of TnpI recombinase protein and DNA substrate in a buffer containing 50 mM Tris-HCl pH 8.0, 25mM KCL, 1.25mM EDTA, 5mM spermidine, 10% glycerol and 25 µg/ml BSA, and incubated at 37 °C for different times. In a preferred embodiment the incubation time is 30 minutes. Preferably, the TnpI recombinase protein is purified. The recombination products may be analysed by restriction enzyme digestion followed by agarose gel electrophoresis of the reactions.
- In various embodiments, for example, the *in vitro* TnpI recombination reaction is used for the construction and manipulation of recombinant DNA molecules *in vitro*. Such methods have been described for use with other site-specific recombinases, such as the Cre/lox system (see U.S. Patent No. 5,851,808, issued Dec. 22, 1998; International Publication No. WO 00/05355, published Feb. 3, 2000; Liu et al., 2000, Methods in Enzymology 328: p530-549). Using the TnpI/TRT system *in vitro*, one can rearrange, shuffle, and subclone DNA molecules from one type of vector into another, without the need for costly restriction enzymes, ligases and time-consuming and labor intensive *in vitro* manipulations. For example, in one embodiment, the TnpI/TRT system may be used to subclone or "shuttle" a nucleotide sequence (or library of nucleotide sequences) of interest from a first DNA molecule (a "donor" vector) into a second DNA molecule (a "recipient" vector), which recipient vector is particularly suited for a desired purpose, such as expression in a particular host cell type. The donor vector comprises a TnpI recombination target site, the gene of interest, an origin of replication, and, optionally, one or more selectable marker genes. The recipient molecule comprises one or more nucleotide regulatory sequences juxtaposed to a TnpI recombination target, an origin of replication, and, optionally, one or more selectable marker genes. The nucleotide regulatory sequence

may be any sequence that may modify, promote or enhance expression of the gene interest in the host cell. Examples of such nucleotide regulatory sequences include, but are not limited to, eukaryotic or prokaryotic transcriptional regulatory sequences such as promoters, enhancer elements, and/or transcription factor binding sites, such as cell-type specific or tissue-specific transcription factor binding sites, translational regulatory elements, and/or post-translational processing sites. Preferably, in this embodiment, where unconstrained recombination activity is desirable, the TnpI recombination target site is a TRT sequence.

In another embodiment, for example, the *in vitro* deletion reaction between TnpI recombination target sites may be used to produce circular DNA molecules devoid of undesired nucleotide elements. Such a method may be used, for example, in the construction of DNA vaccines, where it would be desirable to remove unnecessary vector sequences from a DNA molecule before administration of the DNA vaccine to a subject. For example, such a vector may be constructed by placing the DNA sequence of interest between two directly repeated TnpI recombination target sites, which are later useful for removing the replication origin and resistance marker genes, producing a final DNA vaccine product useful for therapeutic treatment. Preferably, in this embodiment, where the constrained recombination activity may be desirable, the TnpI recombination target is a TRT' sequence.

Finally, the TnpI/TRT system may be used in conjunction with other site specific recombination systems with different specificities, *e.g.*, Cre/lox or Flp/FRT recombinases, to expand the versatility of the *in vitro* methods (Meyers *et al.*, 1998, Nat. Genet. 18:136-41). For example, plasmid vectors comprising both TnpI recombination target sites together with one or more other site-specific recombinase recognition sites could be used to delete, insert, and/or rearrange DNA sequences at particular steps of a multi-step cloning process. Such methods may be particular useful, for example, in the fields of proteomics and directed evolution to construct novel proteins with novel activities which require for multi-step shuffling methods.

6. EXAMPLES

The invention is illustrated by the following experiments, which analyze the site-specific recombinase activity of TnpI both *in vivo* and *in vitro*.

The examples presented hereinbelow demonstrate that TnpI mediates recombination, both *in vivo* and *in vitro*, using two distinct target sites, the minimal TRT site and the full TRT' site, and that TnpI activity at these two distinct sites leads to topologically distinct intermediates and functionally distinct recombinant products. The experiments further demonstrate that TnpI is active in a broad range of host cells, without the need for accessory

factors. As demonstrated herein, these previously unknown abilities of TnpI and its recombination substrates have important implications for the use of TnpI recombinase in genetic engineering.

5 6.1 ANALYSIS OF TNPI-MEDIATED RECOMBINATION *IN VIVO*

One of the limitations of use of other well known recombinases, such as Cre/lox or Flp/FRT, is the complete reversibility of their reaction mechanisms. Consequently, the rate of production of final product is impeded by the rate at which product undergoes the reverse reaction to reform the substrate (Logie and Stewart, 1995, Proc. Natl. Acad. Sci. USA 92: 10 5940-5944). The experiments in this section demonstrate that the reversibility of TnpI-mediated site-specific recombination depends on the nature and structure of the recombination target site. Thus, substrates can be specifically designed according to the desired reversibility of the excision/insertion reaction.

15 6.1.1 DIFFERENTIAL ACTIVITIES OF TRT' AND TRT SUBSTRATE S

Previous reports identified a 249 bp fragment of transposon Tn4430 as the shortest DNA fragment that includes the sequences required for TnpI recombination (See Figure 2; Salamitou *et al.*, 1997, *supra*; Sanchis *et al.*, 1997, *supra*). As depicted in Figure 2, this region contains three distinct TnpI binding sites: a 32 bp inverted repeat sequence, and two 20 downstream 16bp direct repeat sequences. To analyze the requirements for TnpI-mediated recombination, TnpI-mediated recombination was analyzed in the heterologous host *E. coli*.

For heterologous expression, an inducible TnpI expression vector, pYZ-BAD-TnpI, was constructed. pYZ-BAD-TnpI was created by inserting the coding sequence for TnpI, 25 shown in Figure 3, into the vector pBAD24, such that the expression of TnpI was under the control of the arabinose-inducible promoter, P_{BAD}. The resultant vector, pYZ-BAD-TnpI, as shown in Figure 4, comprises P_{BAD} operatively linked to the TnpI coding sequence, a p15A replication origin, a kanamycin resistance selectable marker, and *AraC*, the arabinose-responsive repressor that regulates P_{BAD}. (In addition, pBAD expression vectors have been 30 constructed which express TnpI as a His-tag fusion protein. Both forms of protein were found to be equally active, both *in vivo* and *in vitro*.)

Initially, TnpI-mediated recombination was tested in *E. coli* using a “full-length” TnpI recombination target sequence. Two copies of a 244 bp fragment comprising the left IR and all four TnpI binding sites, called TRT” (see Figure 1A), were cloned into a plasmid 35 in direct repeat orientation and used as a substrate for recombination in *E. coli*. This plasmid construct was then transformed into *E. coli* cells containing the TnpI expression

plasmid pYZ-BAD-TnpI, and induced with arabinose. Using TRT", recombination was detected upon induction of TnpI, indicating that the heterologous host *E. coli* supports TnpI-mediated recombination.

To further refine the sequence requirements of TnpI-mediated recombination, various substrates were tested for recombination activity in *E. coli* cells expressing TnpI. DNA plasmids containing directly repeated copies of TnpI recombination target sites of various lengths were tested as substrates. In particular, plasmids were constructed containing directly repeated copies of either the abbreviated 116bp TnpI recombination target site, TRT' (shown in Figure 1B), containing both the 32 bp inverted repeat sequence and the two downstream 16bp direct repeat sequences, or the shorter 32 bp TnpI recombination target site, TRT (shown in Figure 1C), containing only the 32 bp inverted repeat sequences. Plasmids containing TRT or TRT' sites were introduced into *E. coli* cells in the presence or absence of a TnpI expression plasmid. Plasmid products were then purified from the cells and separated on agarose gels containing ethidium bromide.

The result is shown in Figure 5A-B. As depicted in Figure 5A, complete recombination between a substrate, S, containing the two recombination sites produces two recombination products, P, one of which lacks a plasmid origin (indicated by a filled circle) and is therefore unable to replicate *in vivo*. Products of TnpI-mediated recombination in *E. coli* are shown in the agarose gel depicted in Figure 5B. Plasmids containing TRT or TRT' sites were tested in the presence of TnpI expression. The results of this experiment indicate that DNA plasmids containing directly repeated 116 bp TRT' sites yielded the expected recombination product in the presence of TnpI expression (lane 5), but not in the absence of TnpI expression (lane 4). However, using the DNA plasmid comprising the minimal TRT (lanes 6 and 7), an unexpected result was obtained. Rather than the lower-molecular weight band representing the expected product, a ladder of multiple higher-molecular weight bands was observed upon induction of TnpI expression (lane 7). This ladder of high molecular weight bands represents a series of plasmid multimers, the products of intermolecular recombination, rather than deletion. A small amount of the expected lower molecular weight product is observed seen at the bottom of the ladder.

These unexpected results indicate that the 116 bp TRT and the shorter 32 bp TRT exhibit functionally distinct properties as TnpI recombination substrates. Apparently, when TRT' is used a substrate, the intramolecular (forward) reaction, which yields the two products, is topologically different from the intermolecular (backward) reaction, which recreates the starting material DNA substrate. This may be explained by a difference in the topological states of the TnpI-TRT complex versus TnpI-TRT' protein complexes. The TRT' complex may provide an asymmetric component so that the intermolecular reaction is

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favored over the intramolecular reaction. This topological component is discussed further below (see Section 6.2.3 and Figure 9 below).

In sum, the use of alternative, distinct TnpI recombination target sites allows options for use in genetic engineering. Thus, the use of the full TRT' favors the forward, intramolecular excision reaction, and disfavors the reverse, intermolecular insertion reaction. On the other hand, the use of the full length TRT' can be used when the irreversible intramolecular excision reaction is desired.

10 6.2 ANALYSIS OF TNPI-MEDIATED RECOMBINATION *IN VITRO*

The following *in vitro* recombination experiments were performed to identify the functional domains and *in vitro* requirements of TnpI-mediated recombination.

Importantly, it was found that the purified TnpI is sufficient to promote recombination at the TRT and TRT' sites, albeit with different efficiencies, and that additional auxiliary factors are not required. Topological analysis of the *in vitro* recombination products also revealed that recombination at TRT and TRT' involves the formation of recombination complexes with different level of complexity.

6.2.1 TNPI OVEREXPRESSION AND PURIFICATION

20 To overexpress the TnpI protein in *E. coli*, a Bg/II-Hind/III DNA fragment carrying the TnpI coding sequence was amplified by PCR and inserted into the pBAD/HisA expression vector (Invitrogen). As depicted in Figure 6A (upper panel), the resulting plasmid, pGIV007, encodes a His-tag::TnpI fusion protein, H-TnpI, the expression of which is under the control of the *E. coli* arabinose operon promoter, pBAD. An NcoI deletion of pGIV007 was constructed in order to delete the His-tag region and to generate the plasmid pGIV008, which expresses the wild-type TnpI protein (Figure 6A, lower panel). Cultures of *E. coli* cells containing these two plasmids were induced with 0.2 % L-arabinose, and the expressed proteins were purified (H-TnpI) or partially purified (TnpI) by affinity chromatography on nickel resin, and displayed by SDS PAGE gel electrophoresis as shown in Figure 6B.

6.2.2 DIFFERENTIAL ACTIVITY OF TRT' AND TRT *IN VITRO*

The recombination activity of TnpI and H-TnpI was examined *in vitro*. DNA plasmids containing either two directly repeated copies of the TRT site (pGIV016) or two directly repeated copies of the TRT' site (pGIV014) were used as recombination substrates. As depicted schematically in Figure 7A, complete recombination between the two TRT or

TRT' copies results a deletion reaction, producing two smaller plasmids, each with a single TnpI recombination target site. Recombination reactions were performed with ~ 500 ng of purified recombinase protein and supercoiled DNA in a volume of 20 µl, containing 50 mM Tris-HCl pH 8.0, 25mM KCL, 1.25mM EDTA, 5mM spermidine, 10% glycerol and 25 µg/ml BSA. Reactions were incubated at 37°C for 30 min.

The recombination reactions were then analyzed by the restriction enzyme digestion, followed by electrophoresis in a 0.8 % agarose after digestion with *HindIII*. Since the starting plasmids each contained two *HindIII* sites, digestion with *HindIII* yields two fragments, S1 and S2 (see Figure 7A). However, *HindIII* digestion of the recombination products, each of which contains a single *HindIII* site, yields two distinguishable fragments, P1 and P2 (see Figure 7A). Thus, *HindIII* digestion readily distinguished the starting material from the two products. As shown in the agarose gels in Figure 7B, *HindIII* digestion of the recombination reactions resulted in the expected size fragments corresponding to starting material and recombination products using both TRT and TRT' as substrates. Thus, these results demonstrated that the purified TnpI protein is sufficient to promote efficient recombination at TRT and TRT' *in vitro*, without requiring additional host factors.

Next, a kinetic time-course analysis of TnpI-mediated recombination *in vitro* reactions was performed using TRT and TRT'. Figure 7C shows the results of a time course analysis of recombination at TRT (squares) and TRT' (diamonds). For each time point, the proportion of the products was quantified by densitometry analysis of an electrophoresis gel containing *HindIII*-digested reactions. This analysis revealed that recombination of a plasmid carrying two directly repeated TRT' sequences is faster than recombination of a similar plasmid containing the TRT core sequence, indicating that the additional TnpI binding sites in TRT' stimulated recombination. Similar recombination activity was observed for the wild-type and His-tagged TnpI proteins, demonstrating that the recombinase tolerates N-terminal peptide fusions.

6.2.3 RECOMBINATION AT TRT AND TRT' INVOLVES THE FORMATION OF RECOMBINATION COMPLEXES WITH DIFFERENT LEVELS OF COMPLEXITY

The topology of *in vitro* recombination products was analyzed by treating the reactions with DNase I in the presence of ethidium bromide. This treatment introduces single nicks in DNA, allowing removal of supercoiling while perserving the intercatenation nodes introduced into the substrate during recombination (see Figure 8A). Plasmid substrates were incubated in the presence or absence of H-TnpI, and then treated in reactions with 1 µg/ml of DNase I (+) and 0.3 mg/ml of ethidium bromide, or without

DNase I (-), as indicated. Nicked reactions were then analyzed by high resolution agarose gel electrophoresis (0.7% agarose) to compare the complexity of the products resulting from TRT or TRT' recombination.

As shown in Figure 8A, intramolecular recombination between directly repeated TRT sequences generated a variety of deletion products (catenanes) in which the two DNA circles remained interlinked a certain number (*i.e.*, 2, 4, 6, *etc.*; labeled 2, 4, and 6 in Figure 8A) of times. Recombination also produced faint bands corresponding to knotted DNA molecules containing 3, 5, *etc.* nodes (labeled 3 and 5 in Figure 8A). Such knots arose from consecutive recombination events using the initial catenated products as a substrate. These results indicate that TRT recombination occurs freely by random collision between recombination sites.

In contrast, the TRT' recombination substrate yielded exclusively 2-noded catenane products (Figure 8B). This result indicated that recombination is catalyzed within a protein-DNA complex having a specific geometry. Assembly of the recombination complex may involve multiple interactions between TnpI molecules bound onto the inverted and direct repeats of TRT'. According to the current model, depicted in Figure 9, the topology of the DNA within this complex is such that it can only form efficiently if the two recombination sites are present in tandem on a same DNA molecule, thereby providing directionality to the recombination reaction. When TnpI is also bound to the direct repeats (DR1, DR2), a specific higher order wrapping is created in addition to the one formed when TnpI is bound to TRT.

6.3 TNPI-MEDIATED RECOMBINATION IN EUKARYOTIC CELLS

The experiments in this section demonstrate the ability of TnpI to mediate site-specific recombination in eukaryotic cells. A eukaryotic TnpI recombination reporter cell line was constructed by introducing pSVpaT, depicted in Figure 10, into mouse ES cells. As shown in Figure 10, pSVpaT contains an SV40 promoter, a puromycin resistance gene flanked by two direct copies of a 32 bp TRT sequence containing the inverted repeat, the β -galactosidase gene (*lacZ*), and the chloramphenicol resistance gene.

The nucleotide sequence encoding TnpI was cloned into the eukaryotic expression plasmid pCAGGS to construct the eukaryotic TnpI expression plasmid pCAGGS/TnpI, which is depicted in Figure 11. pCAGGS includes the TnpI coding sequence, the expression of which is driven by the chicken beta-actin promoter P_{CBA} .

ES cells containing stably integrated pSVpaT sequences were selected for by selecting for puromycin resistance. Before TnpI-mediated recombination, these TnpI reporter ES cells do not express LacZ (see Figure 12, top). However, TnpI-mediated

recombination removes the puromycin resistance gene, which lies between the SV40 promoter and *lacZ*, and juxtaposes the *lacZ* gene next to the SV40 promoter (see Figure 12, bottom). Thus, recombination results in the expression of *lacZ*, which can be detected by the appearance of blue colonies upon the introduction of lactose.

5 Figure 13 shows the results of this experiment. Introduction of the pCAGGS/TnpI expression vector into the TnpI reporter ES cells resulted in the expression of LacZ, as indicated by the presence of blue colonies, shown in Figure 13.

 This previously unreported ability of TnpI to catalyze site-specific recombination in eukaryotic hosts expands the commercial potential of TnpI for genetic engineering.

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 The invention described and claimed herein is not to be limited in scope by the specific embodiments herein disclosed since these embodiments are intended as illustration of several aspects of the invention. Any equivalent embodiments are intended to be within the scope of this invention. Indeed, various modifications of the invention in addition to
15 those shown and described herein will become apparent to those skilled in the art from the foregoing description. Such modifications are also intended to fall within the scope of the appended claims. Throughout this application various references are cited, including patent applications and publications, the contents of each of which is hereby incorporated by reference into the present application in its entirety for all purposes.

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